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Results of Flight Tests to Investigate Civil Certification of Sidestick Controllers for Helicopters

Roger H. Hoh
Hoh Aeronautics Inc.
Lomita, CA

Stewart Baillie and Stan Kereliuk
National Research Council
Ottawa Canada

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Final Report

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16. Abstract

This report presents the results of flight tests conducted to compare two sidestick controllers with a conventional rotorcraft cyclic, collective, and pedal controller configuration. The sidesticks were tested in several modes ranging from full control of all rotorcraft angular degrees of freedom plus height, to control of just pitch and roll. The emphasis in this document is on issues related to civil certification, including exposure of FAA and Transport Canada pilots to sidesticks.

The task emphasized maneuvering in visual meteorological conditions (VMC) very close to the ground, although some traffic patterns and autorotations were flown. Each pilot also flew one or two decelerating instrument approaches with each controller. The test helicopter was the National Research Council of Canada (NRC) variable stability Bell 205A, which was augmented with rate feedback to produce angular response characteristics similar to the Sikorsky S-76. Identical rotorcraft dynamics were used for all of the tested controller configurations.

This report presents interpretations of the data believed to be directly applicable to U.S. civil certification. See also "An Investigation into the Use of Side-Arm Control for Civil Applications," NRC, IAR-AN-67, June 1990.

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I INTRODUCTION

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The tasks emphasized maneuvering in visual meteorological conditions (VMC) very close to the ground, although some traffic patterns and autorotations were flown. Each pilot also flew one or two decelerating instrument approaches with each controller.

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This program was conducted jointly by the FAA and the Canadian National Research Council (NRC) under a memorandum of agreement between those two agencies. Hoh Aeronautics Inc. (HAI) provided technical assistance in developing the test plan and in the conduct of the experiment. This report has been prepared by HAI, and presents interpretations of the data felt to be directly applicable to U.S. civil certification. The reader should refer to the NRC report (Reference 2) for a detailed description of the experiment, and experimental results.

II BACKGROUND

The NRC has done considerable work on the development and evaluation of 4-axis sidesticks for rotorcraft, e.g., see References 1 and 3. That work included a comparison of the sidesticks and conventional controllers utilized in this experiment. However, most of the previous testing was done in the context of military missions and requirements. The present testing was conducted to determine the viability of using the sidestick for civilian rotorcraft operations.

The results of previous comparisons (Reference 1) have indicated that there was no significant difference between the 4-axis sidestick and conventional controllers in terms of handling qualities and performance. The primary objective of the present work was to determine if this result can be extended to civilian operations. In that context three of the evaluation pilots were (and still are) FAA certification pilots, and one is employed by Transport Canada, and has extensive certification experience in Canada.

III EXPERIMENTAL SCENARIO

The baseline controller configuration consisted of the usual cyclic, collective, and pedal found in all current helicopters. Two sidesticks were tested, one with a moderate amount of travel (sidestick A) and one with very limited travel (sidestick B). The important characteristics of these sidesticks are summarized in Table 1. They are described in greater detail in References 1 and 2).

Table 1. Characteristics of Tested Controllers

CONVENTIONAL CONTROLLERS				
Axis	Breakout	Gradient		Travel
	lbs	lb/in	lbs/ % of full travel	inches
Pitch	0.50	1.0	0.060	± 6.0
Roll	0.25	1.0	0.065	± 6.5
Yaw	7.0	15	0.675	±4.5
CONTROLLER A				
Axis	Breakout	Gradient		Travel
	in-lb	in-lb/deg	in-lb/% of full travel	deg
Pitch	1.7 Nominal 2.3 As tested	0.16 Nominal 0.09 As tested	0.024 Nominal 0.014 As tested	± 15
Roll	0.95 Nominal 1.25 As tested	0.23 Nominal 0.103 As tested	0.039 Nominal 0.018 As tested	± 17
Yaw	1.9 Nominal 1.9 As tested	0.13 Nominal 0.17 As tested	.016 Nominal 0.020 As tested	± 12
Heave	0.0 lb Nominal 0.7 lb As tested	0.0 Nominal 2.2 lb/in As tested	0.0 Nominal .022 lb/% As tested	± 1.0 inch
CONTROLLER B				
Axis	Breakout	Gradient		Travel
	lb	lb/in	lb/ % of full travel	in
Pitch	0.3	15.0	.075	0.50
Roll	0.3	15.0	.075	0.50
Yaw	0.75	Not defined	.075	0.0
Heave	0.075	Not defined	.075	0.0

It is important to note that sidestick A had significantly higher breakout and decreased gradient from its nominal design value. While this drift in parameters was unintentional, it provided some unexpected data. As will be shown later, the change in parameters in sidestick A resulted in a significant degradation in handling qualities.

The cockpit controller configurations that were tested are summarized below.

- Conventional cyclic stick, collective, and pedals.
- Sidesticks A and B with pitch and roll active, and yaw and heave disconnected (2+1+1) [1]; pilot controlled yaw and heave with standard pedals and collective respectively.
- Sidesticks A and B with pitch, roll, and collective active, and yaw disconnected (3+1)p; pilot controlled yaw with standard pedals.
- Sidesticks A and B with pitch, roll, and yaw active, and collective disconnected (3+1)c; pilot controlled heave with standard collective.

The order of presentation of these controller configurations was deemed to be critical, since the evaluation pilots were required to retrain to a new way of flying with each configuration, especially the 4+0 configurations. On that basis, the 4+0 was always presented first, thereby allowing time during the experiment to make repeat runs to examine the effect of training. The order of presentation of each of the controllers is given in Table 2. The cases were run so that the pilots were introduced to the full (4+0) sidestick at the beginning, and again at the end of the tests i.e., after they had between 10 and 12 hours of sidestick experience. Finally, each pilot was given an opportunity to fly the conventional controls at the end of the tests to allow a direct comparison with the full (4+0) sidestick after a reasonable amount of sidestick training had been completed. The intermediate configurations were not repeated because they were clearly in the certifiable range.

It should be noted that since sidestick A was flown in a degraded mode (see Table 1), and therefore comparisons of the sidestick controller vs. the conventional controllers should be based on sidestick B.

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[1] Notation: (2+1+1) infers control of pitch and roll on the sidestick and yaw and heave with the conventional pedals and collective.

(3+1)p infers control of pitch, roll, and heave on the sidestick, and yaw on the pedals.

(3+1)c infers control of pitch, roll, and yaw on the sidestick, and heave on the standard collective controller.

(4+0) infers control of pitch, roll, yaw, and heave on a single sidestick controller.

Table 2. Order of Presentation of Each of the Controller Configurations

PILOT A	PILOT B	PILOT C	PILOT D
Conventional	Conventional	Conventional	Conventional
B - (4+0)	A - (4+0)	A - (4+0)	B - (4+0)
B - (3+1)c	A - (4+0)	A - (4+0)	B - (4+0)
B - (3+1)p	A - (3+1)c	A - (3+1)c	B - (3+1)c
B - (2+1+1)	A - (3+1)p	A - (3+1)p	B - (3+1)p
A - (4+0)	A - (2+1+1)	A - (2+1+1)	B - (2+1+1)
A - (4+0)	B - (4+0)	B - (4+0)	A - (4+0)
A - (2+1+1)	B - (3+1)p	B - (3+1)c	A - (3+1)c
A - (3+1)p	B - (3+1)c	B - (3+1)p	A - (3+1)p
A - (3+1)c	B - (2+1+1)	B - (2+1+1)	A - (2+1+1)
A - (4+0)	B - (4+0)	B - (4+0)	A - (4+0)
B - (4+0)	A - (4+0)	Conventional	A - (4+0)
Conventional	Conventional	A - (4+0)	B - (4+0)
			Conventional

The flying qualities tasks were laid-out on a course so that the pilots flew the following maneuvers without interruption over the course illustrated in Figure 1.

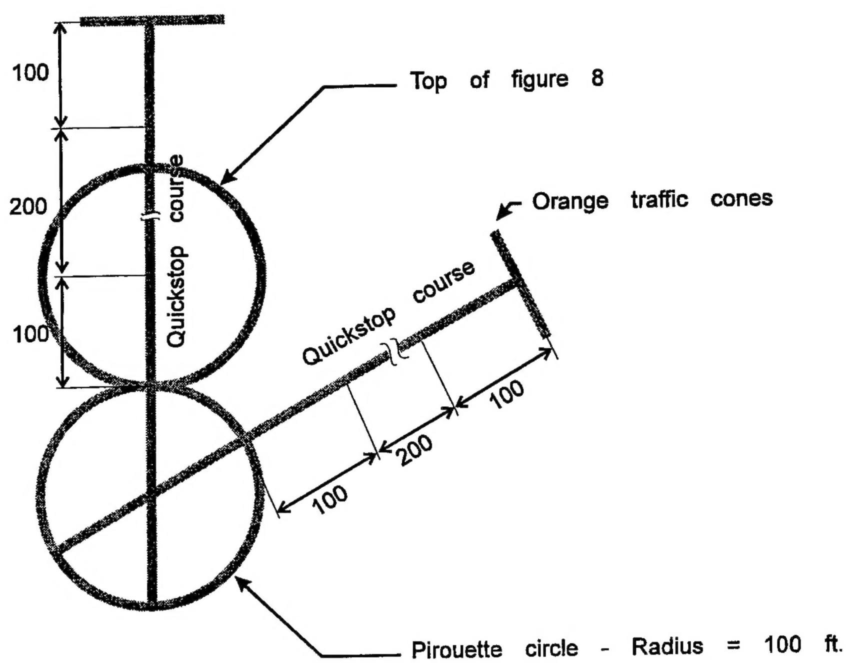

Figure 1. Diagram of Test Course Used in Evaluations (All dimensions in feet)

The flying qualities tasks are summarized below in the order flown.

1. Precision hover.
2. Vertical landing.
3. Sidestep (very non-aggressive, more like a lateral taxi).
4. Divided attention hover - tune a communications radio while hovering.
5. Repeat the vertical landing maneuver.
6. Repeat the sidestep maneuver.
7. Pirouette to the right over circle shown in Figure 1 (complete in 45 sec or less).
8. Figure 8 maneuver over two circles shown in Figure 1.
9. Quickstop over "quickstop segment" noted in Figure 1.
10. Slope landing on slope of approximately 4 degrees.
11. Pattern - obstacle clearance takeoff, climb to downwind leg, and make a steep approach back to the point of departure (to a stabilized hover).
12. Autorotation entry followed by back-to-back 90 degree turns (flown at altitude).
13. Decelerating instrument approach on flight director. (Note: flown at altitude to avoid noise problems in the test area).

The pilots were required to fly the course three times before assigning subjective handling qualities ratings (HQRs) from the well-known Cooper Harper scale in Figure 2. Each of the maneuvers was rated separately.

IV RESULTS

The results of this experiment are summarized in Table 3, and in Figure 3. Some observations from this data are presented below.

A. Certification Issues

Based on the results of this experiment, sidestick controllers are a viable alternative to the conventional centerstick for the civil helicopter. This observation includes the 4-axis controller, with the caveat that there are significant training requirements that could have an impact on safety, especially for low time helicopter pilots. This is based on the data for sidestick B in Table 1 wherein two pilots gave an unqualified yes, and two felt that the 4-axis sidestick controller certification was marginal. Pilot D changed from marginal to yes on his third 4-axis controller flight, but it must be noted that this flight was conducted on a calm day. All four pilots agreed that the 3-axis sidestick controller with conventional pedals was certifiable, whereas the 3-axis sidestick controller with conventional collective was rated as certifiable by three pilots and marginal by one pilot.[2] All of the pilots agreed that the 2-axis sidestick controller was certifiable after only one evaluation (i.e., with very little training).

[2] It is notable that the marginal rating was given after only one evaluation. This may have improved to certifiable after additional training.

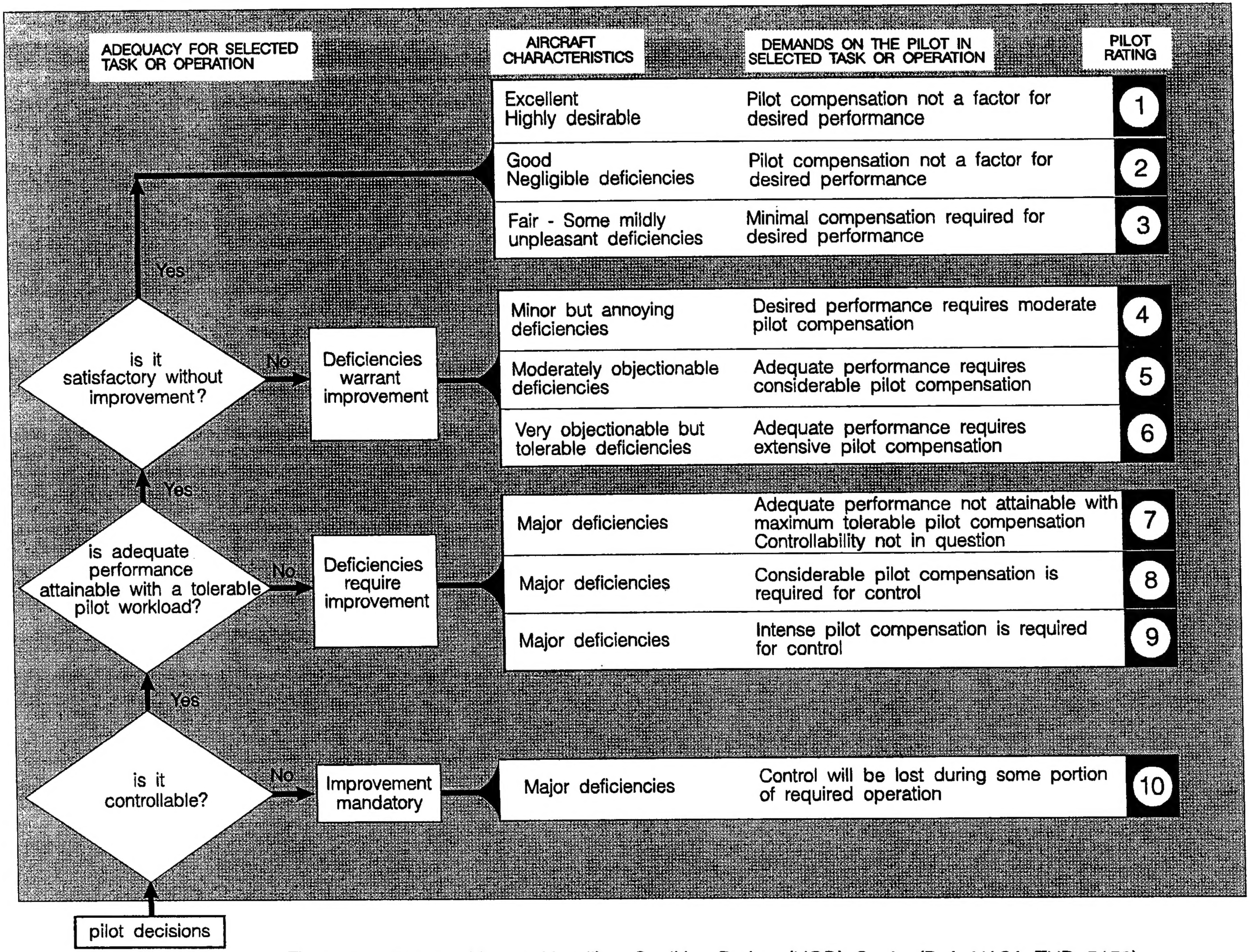

Figure 2. Cooper Harper Handling Qualities Rating (HQR) Scale (Ref. NASA TND 5153)

TABLE 3 COOPER HARPER HANDLING QUALITIES RATINGS FOR ALL TESTED CONTROLLERS AND TASKS

CONTROLLER/PILOT	DECISION TO CERTIFY	HOVER	LANDING	SIDESTEP	D.A. HOVER	PIROUETTE	FIGURE 8	QUICKSTOP	SLOPE LND. AND T.O.	PATTERN	AUTO ROT.	IMC APP.
CONVENTIONAL CONTROLLER												
PILOT A	YES/YES	3,3	3,3	3,4	2,4	4,3	3,2	3,2	3,3	2,3	2	5
PILOT B	MARGINAL/YES	3,3	3,3	2,3	4,4	2,4	2,4	3,3	3,4/3	2,2	2	2
PILOT C	YES/YES	3,2,5	4,2	3,2.5	6,4	5,4	4,3	4.5,2.5	6,4/2	2,3	4	N/A
PILOT D	YES/YES	4,3	4,3	3,2.5	4,3	3,3	3,3	3,2.5	2,3	2,3	3	3
CONTROLLER A (4+0)												
PILOT A	NO/NO/NO	4,4,3	5,4,3	7,7,5	4,4,3	8,7,5	7,7,4	8,7,6	6,6,3	5,6	N/A	6
PILOT B	NO/NO/NO	3,4,3	4,4,4	4/5,5,5	4,6,5	4,5,6	5,6,6	7,8,7	4/5,6,7/5	4,5/4,4/3	7	5
PILOT C	MARG/MARG/MARG	5,4,4	6,5,3	5,4,4.5	5,5,4	7.5,6,6	6,5,5	7,7,7	6,6,5	3,3,3	5	5
PILOT D	NO/NO/NO	5	5.5	5	5	7	7	4	6	3	4.5	4
CONTROLLER B (4+0)												
PILOT A	YES/YES	2,3	3,3	3,4	2,3	3,3	2,2	3,5	2,3	3,3	8	6,3
PILOT B	MARG/MARG	3,2	3,2	3,3	4,4	6,4,4	4,4	5,3	4/3,3/3	4/3,3/2	4	3
PILOT C	YES/YES	2,2	3,1.5	2,2	3,2.5	3,3	3,3	3,3	4,3	2,2	3	3
PILOT D	MARG/MARG/YES	4,3,3	4,3,3	4,3,3	3,4,4	7,7,3	6,3,3	4,3,4	2,2,2	2/3,2/3,3/3	7	3
CONTROLLER A (3+1)P												
PILOT A	YES	2	3	5	3	4	4	4	3	2	N/A	N/A
PILOT B	MARGINAL	4	4	4	5	5	5	7	6	4/4	N/A	N/A
PILOT C	MARGINAL	4	5	4	4	5	5	4	5.5	2	N/A	N/A
PILOT D	NO	4.5	4.5	5	4	6	6	5	4	3/3	N/A	N/A
CONTROLLER B (3+1)P												
PILOT A	YES	2	3	3	2	3	3	2	3	3	N/A	N/A
PILOT B	YES	3	3	3	4	4	4	3	4/3	4/3	N/A	N/A
PILOT C	YES	3	3	3	3	4	4	4.5	4	2	N/A	N/A
PILOT D	YES	4	4	3	4	6	5	3	2	2/3	N/A	N/A
CONTROLLER A (3+1)C												
PILOT A	YES	3	2	3	4	3	3	3	2	3	N/A	N/A
PILOT B	YES	3	3	3	4	5	4	5	5	3/3	N/A	N/A
PILOT C	MARG	3	3	3	4	5	5	4	4	2	N/A	N/A
PILOT D	NO	5	5	4.5	5	5.5	5.5	4	4	3/4	N/A	N/A
CONTROLLER B (3+1)C												
PILOT A	YES	3	3	3/4	2	2	2	3	3	3	N/A	N/A
PILOT B	YES	2	2	3	4	4	4	3	3/2	3/2	N/A	N/A
PILOT C	YES	2	2	2	3	3	3	3	2.5	2	N/A	N/A
PILOT D	MARG	3	3	3	4	7	4	4	2	2/3	N/A	N/A
CONTROLLER A (2+1+1)												
PILOT A	YES	3	3	4	3	4	3	4	3	2	N/A	N/A
PILOT B	YES	3	3	3	4	4	3	4	3	3/2	N/A	N/A
PILOT C	YES	3	3	3	3	4	4	3	4	2	N/A	N/A
PILOT D	NO	4	4	5	4.5	5	5	3	4	2/3	N/A	N/A
CONTROLLER B (2+1+1)												
PILOT A	YES	3	3	3	3	3	3	2	3	2	N/A	N/A
PILOT B	YES	2	2	3	4	4	4	3	3/2	2/2	N/A	N/A
PILOT C	YES	2	2	2.5	4	3	3	3	3	2	N/A	N/A
PILOT D	YES	3	3	2	4	5.5	4	3	2	2/3	N/A	N/A

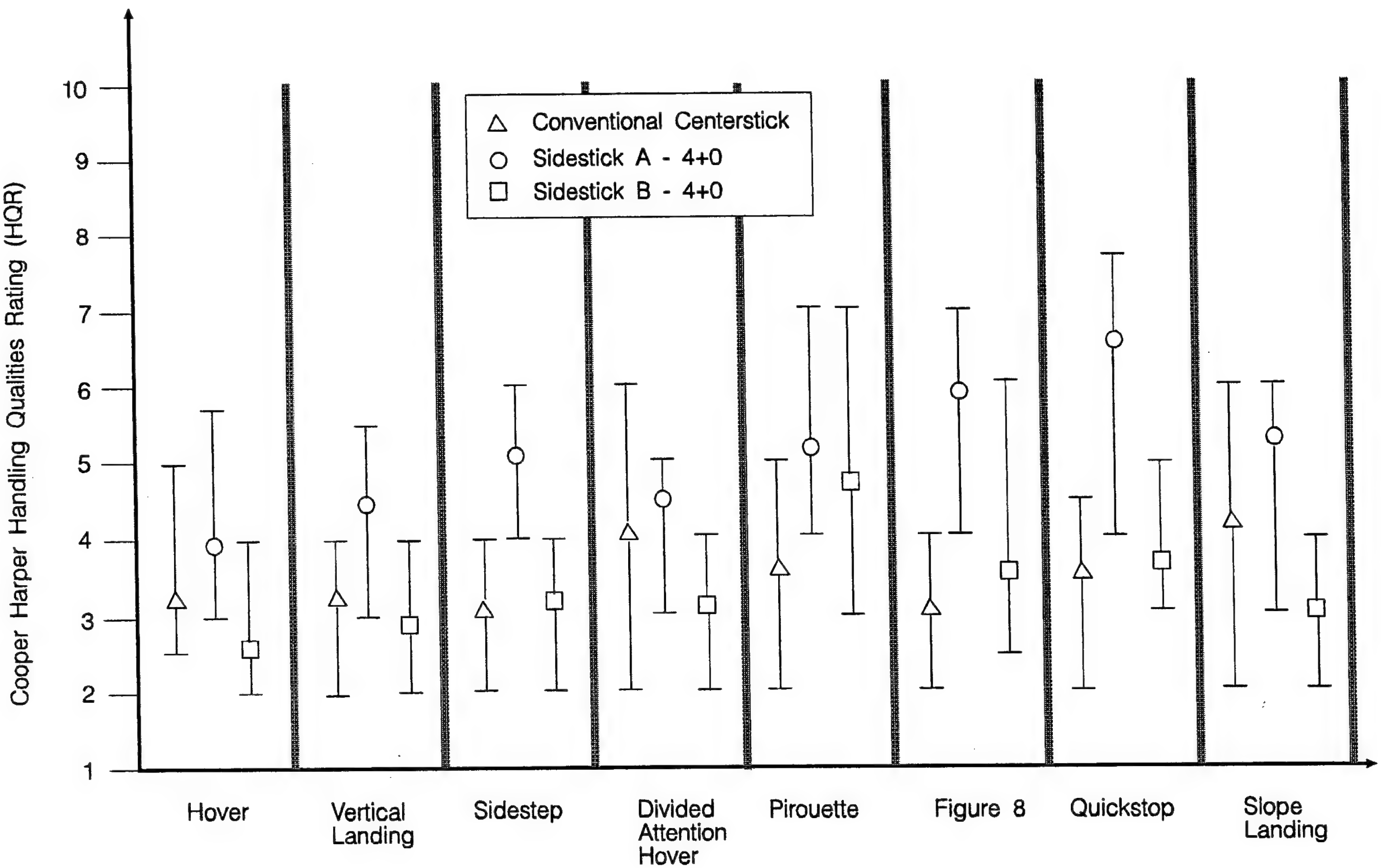

Figure 3. Pilot Ratings For 4+0 Sidesticks and Conventional Controls

Experience gained during this experiment indicates that certification tests of a sidestick controller should focus on multi-axis tasks (e.g., the pirouette), the effect of changes in breakout and gradient, maneuvering in strong winds, and autorotation. These issues are discussed in more detail in the following paragraphs.

B. Autorotation

Some problems were encountered during autorotations with the vertical axis of the 4-axis sidestick controllers. Pilots A and D felt the problems were highly significant (HQRs of 7 and 8) and pilots B and C did not (HQRs 4 and 5), see Table 1, sidestick B. The problem was related to control of rotor RPM. Excerpts from the pilot commentary are given below for sidestick B (sidestick A had all of the problems noted above which tended to obscure the autorotation issue, and is therefore not discussed).

- Pilot A - It is very difficult to select a power position that gives good RPM (rotor revolutions per minute) control once the autorotation was entered and the rotor was in the green, HQR = 8. This was alleviated to some extent by turning off the parallel integrator, HQR = 6. (discussed below).
- Pilot B - Quite comfortable, time to look outside cockpit and monitor RPM. Changed airspeed on second autorotation, and RPM was easy to control. Initial rate of collective deflection was difficult to judge on first entry, but worked out fine on second, HQR = 4.
- Pilot C - HQR = 4 only because of complexity of maneuver. Rotor RPM good and conventional, HQR = 3. Controllability no problem if aggressive i.e., large deflections. Would prefer more collective feel for this maneuver.
- Pilot D - Collective control very poor; no way to tell if it's down, and no tactile cues for RPM control. Rotor RPM could be kept in the green in turns, but required constant attention, HQR=7.

Because of the inherent limited vertical motion of the sidestick controller, it is necessary to incorporate a parallel integrator in the heave axis of the flight control system. Such an integrator produces phase lag, which theoretically should result in less precise control of altitude and rotor RPM (or equal precision with increased workload). Some pilots noticed this potential deficiency, and some apparently did not. Work done in support of the military flying qualities specification for rotorcraft indicated that the required heave damping (Z_W) for HQRs of 3 or better is only -0.20/sec. Since most rotorcraft have a natural heave damping of -0.35 or better, some phase lag in the vertical axis may be acceptable. However, the issue of rotor RPM control during autorotation, and height control for hovering autorotations (not tested here, but requires good precision in altitude) should be carefully tested during the certification of a sidestick collective controller.

C. Training Effects

Ratings for the pirouette maneuver were downgraded more for the 4-axis sidesticks than for the conventional controls during the initial trials. The pirouette maneuver was selected for its demanding requirement for coordination in all axes, and the effect of training would be expected to be significant. The pilot commentary indicated the following problems.

- There were significant yaw control problems during the tailwind portion of the maneuver, and heading response tended to be jerky and abrupt. Some of the rating spread may be due to differences in wind conditions as well as training.
- Large changes in pitch attitude (on the order of 10 degrees) were required when changing from a tailwind to a headwind in the Bell 205A. This causes pilot workload to be very high in a wind.

- Altitude control problems with the sidestick (both A and B) were mentioned a number of times, especially in a moderate wind. This was apparently due to a requirement for a rapid large increase in collective as tail moved into wind.
- The lack of tactile cues as to the location of the controls was cited as a factor by several pilots, especially for the collective axis.

It is well known that training can have a dramatic effect on handling qualities ratings (see Reference 4). The pilot ratings for each successive trial using the 4-axis sidestick to accomplish the pirouette are shown in Figure 4. For sidestick B, the effects of training appear to be significant for pilots B and D. Once the required training was accomplished, the ratings for this sidestick were as good as for conventional controls. Pilot B flew his last pirouette in 15 knot winds, and commented that the power changes with wind azimuth were "no problem." Pilot D flew his last pirouette in calm winds, which probably had some influence on the drastic improvement in rating (HQR from 7 to 3). For sidestick A, the training, which could be accomplished within the test period was not adequate for acceptable ratings. This would indicate that the controller had fundamental problems (discussed in the following paragraph).

D. Effect of Variation in Breakout and Gradient from Design Value (sidestick A).

Sidestick A was tested in a previous experiment (see Reference 1), and found to result in reasonable and acceptable HQRs, e.g., average rating of 3.6 as a 4-axis controller for the pirouette maneuver. Sidestick B was also tested in Reference 1, and was not rated substantially different than sidestick A (the autorotation maneuver was not tested in Reference 1).

As discussed in Section III, the breakout and gradient of sidestick A had drifted considerably from the values used in the Reference 1 tests, resulting in an increase in breakout of approximately 30%, and a decease in the gradient of 50% in pitch and roll. Numerous pilot comments were made relative to excessive breakout, combined with a low gradient indicating that the pilots are sensitive to these parameters. The breakout and gradient of this sidestick controller is apparently a very strong factor in the aircraft handling. It cannot be determined from the existing data whether this is a generic effect for all sidestick controllers. Therefore, certification testing should determine the vulnerability of the controller to changes in breakout and gradient, and if warranted, the controller should be flown in a degraded condition.

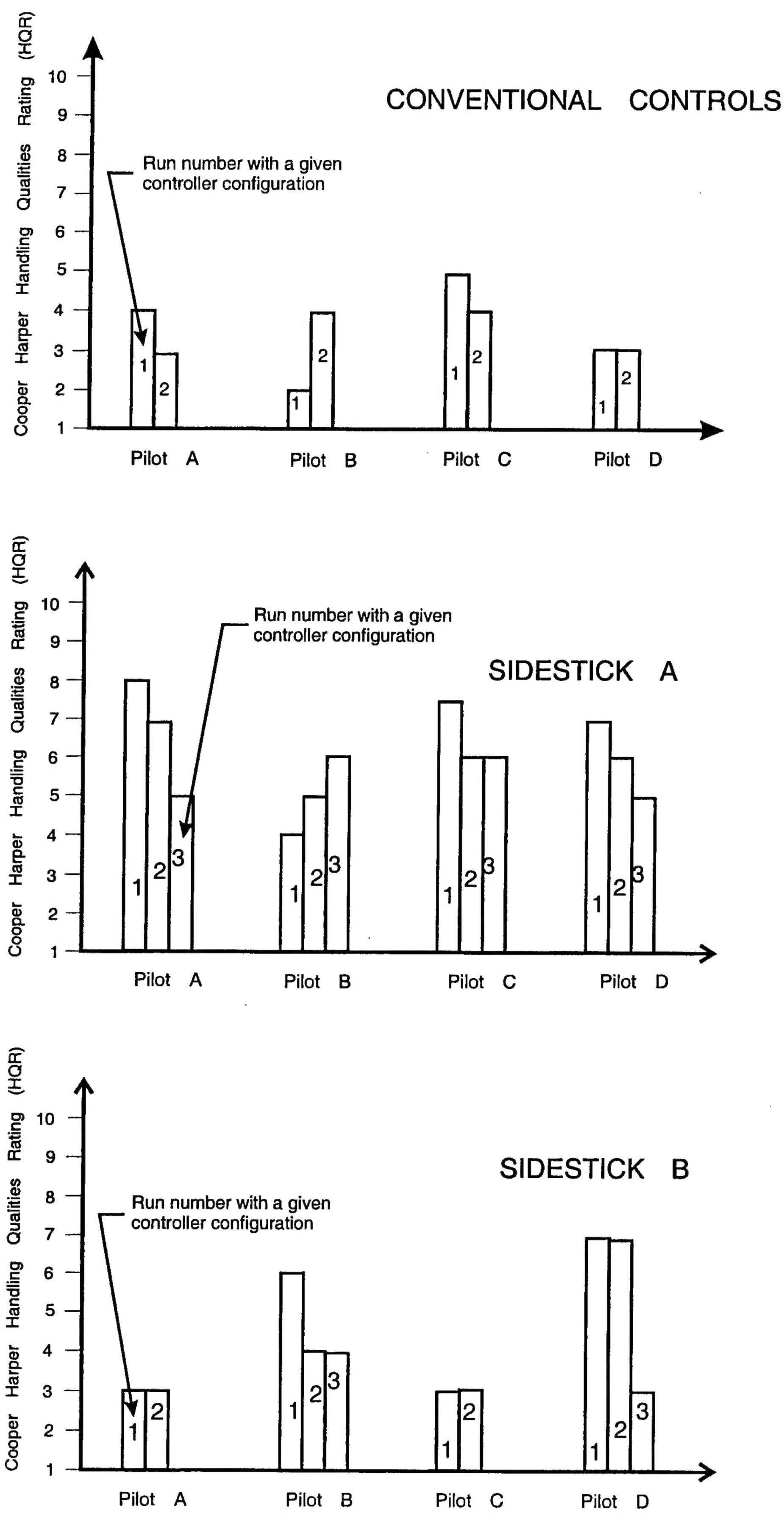

Figure 4 Learning Effects for Pirouette Task

V CONCLUSIONS

The conclusions from this flight test experiment are summarized as follows.

- After about 10 to 12 hours of training, the pilot ratings for a well designed sidestick in the four, three, and two axis configurations are essentially the same as for conventional controls, which is in agreement with the Reference 1 results.
- There is some evidence that autorotation could be a problem for the 4-axis sidestick.
- The pirouette exposed problems with the sidestick that were not apparent with the conventional controls. This may have been a training effect, i.e., the maneuver requires coordination in all three axes, which could require more training than was available. On the other hand, it is possible that the basic workload is higher when controlling multiple axes with one hand, than with both hands and feet.
- The ratings for sidestick A were significantly degraded in the four and three axis configurations. This was apparently due to a change in the breakout and gradient from the nominal design specification (see Table 1).
- Certification flight testing of sidesticks should focus on multi-axis tasks, the effect of changes in breakout and gradient, maneuvering in strong winds, and autorotation.

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